THIN FILM PERIPHERAL NERVE ELECTRODE

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by

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1.0 BACKGROUND

A program to develop a functional neuromuscular system (FNS) capable of graded and stable activation of hand muscles for the restoration of grasp in quadriplegic individuals is being undertaken. The objective of the program is the development of a thin film nerve cuff electrode and the demonstration of the efficacy of the electrode for grasp in an *in vivo* study using a raccoon model. The cuff electrodes are fabricated by vacuum depositing metal films on thin sheets of FEP Teflon and photolithographically patterning the leads and charge injection sites. The patterned substrate is then thermally sealed with a second polymer layer to electronically isolate the leads from the physiological environment. Once all planar fabrication processes, i.e., photolithography, vacuum deposition, and etching have been completed, the electrode is cut out of the substrate and the desired cuff and lead geometries created by thermoforming.

An example of an electrode in planar geometry prior to thermoforming the cuff is shown in Fig. 1. The leads and charge injection sites are patterned on a large polymer substrate with the leads extending to a bonding pad located several centimeters from the cuff. Four charge injection sites, designed to evaluate anodal steering, are shown on the cuff.

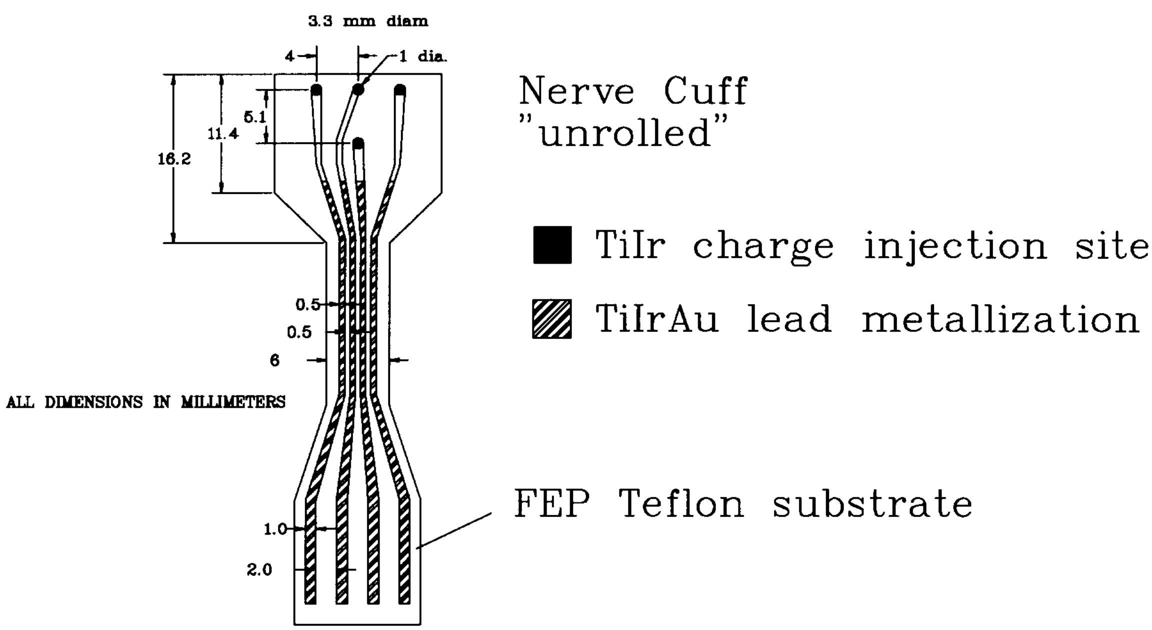

Figure 1. A thermoformable nerve cuff having four charge injection sites in a geometry suitable for evaluating anodal steering.

2.0 TECHNICAL PROGRESS

In Tri-Annual Report No. 4 (June, 1995) and No. 5 (February, 1996), the anatomy of the raccoon forearm and the functional response obtained with various stimulation methods were described. The stimulation methods were the following: intramuscular electrodes implanted in forearm muscles; bipolar hook electrodes on the deep and superficial median nerve branches; and, a 12-electrode silastic nerve cuff implanted around both branches of the median nerve. The intramuscular electrodes were implanted into four muscle groups in the forearm: the pronator teres (PT); the flexor carpi radialis (FCR); and a group consisting of the palmaris longus, flexor digitorium superficialis and the thumb flexor (PL, FDS, TF). Stimulation of PT induced pronation and some wrist flexion while stimulation of FCR induced wrist flexion with some pronation. Stimulation of PL-FDS-TF induced flexion of all the digits and some wrist flexion. The response of flexor digitorium profundus FDP to stimulation was indistinguishable from the PL-FDS-TF muscle group. The innervation of these muscle groups by the branches of the median nerve was also identified. The superficial median nerve branch (median S) innervates PT, FCR, and PL while the deep branch (median D) innervates FDS, FDP and TF. Both the S and D branches innervate the pronator quadratus (PQ).

When the S and D branches of the median nerve were stimulated independently with hook electrodes, the primary functional response was pronation for the S branch and wrist and digit flexion for the D branch. When both branches of the median nerve were placed inside a 12-electrode nerve cuff (4 longitudinal tripoles), a similar pattern of selectivity was obtained. Stimulation with the tripole closest to the S branch produced pronation while stimulation with the other tripoles produced either elbow flexion or wrist and digit flexion. Measurements of tendon force showed that FCR or PL could be selectively recruited from different tripoles. However, the position of the tripoles relative to the fascicles being selectively activated was not well correlated. The lack of correlation can be attributed to several factors including: the difficulty in maintaining the geometric relationship between the nerve and the electrodes during explantation and histology; innervation of some muscles by fibers from both nerve branches; and, the electrically inhomogeneous medium created by having two individual nerve branches within one cuff. Visual observation of paw movement also showed selectivity for flexion and pronation with the nerve cuff electrode. Anodal steering currents reduced the threshold for recruitment but had no observable effect on the gross movements of the paw.

An FEP Teflon nerve cuff electrode with the design shown in Fig. 1 was evaluated acutely in the raccoon. The electrode had a single longitudinal tripole with a 180° transverse electrode for anodal steering. The cuff was manually rotated into each quadrant of the nerve pair (S and D branches) to simulate a 12-electrode cuff. The tendon forces generated by different muscles for the 12-electrode silastic cuff and the 4-electrode FEP Teflon cuff are compared in Figs. 2 and 3, respectively. In both cases, selective recruitment of PT and FCR was obtained. The threshold currents for PT and FCR recruitment observed with the FEP Teflon cuff were about half those observed with the silastic cuff. The electrodes were 1 mm diameter Pt foil on the silastic cuff and 1 mm diameter Ir (slightly activated) on the FEP Teflon cuff. For both electrodes, the stimulation waveform comprised 100 μs cathodal pulses at 20 pps, applied for 1 s. The central electrode of the tripole was the cathode while the outer electrodes served as a common anode. In general, the recruitment response of the FEP Teflon and silastic cuffs were quite similar, showing selectivity for the same muscle groups at comparable force levels.

Although the geometry of the FEP Teflon electrode was adequate for acute studies, the musculature surrounding the nerves at the implantation site prevented convenient routing of the large tab that extends perpendicular to the nerves. It was judged likely that, during chronic studies, the tab would move with the muscles resulting in mechanical trauma to the nerve. A second nerve cuff was designed with a tab running parallel to the nerve. The layout of the metallization for the redesigned nerve cuff is shown in Fig. 4. Three metallization patterns intended for nerve diameters of 2, 2.5, and 3 mm are shown. The nerve cuff has four 1 mm diameter electrodes arranged circumneurally. Electrical connection to the cuff was made with 316 LVM stainless steel lead wires cemented to the bonding pads with Ag-loaded epoxy. The connections were sealed with silastic (NuSil MED 4210).

Electrodes of the design shown in Fig. 4 were fabricated for chronic implantation. Prior to implantation, each charge injection site on the electrode was tested *in vitro* in Ar sparged PBS. The test protocol involved cyclic voltammetry for a period of 15 minutes at a sweep rate of 50 mV/s between limits of -0.6 V and 0.8 V versus the Ag/AgCl reference electrode. A comparison

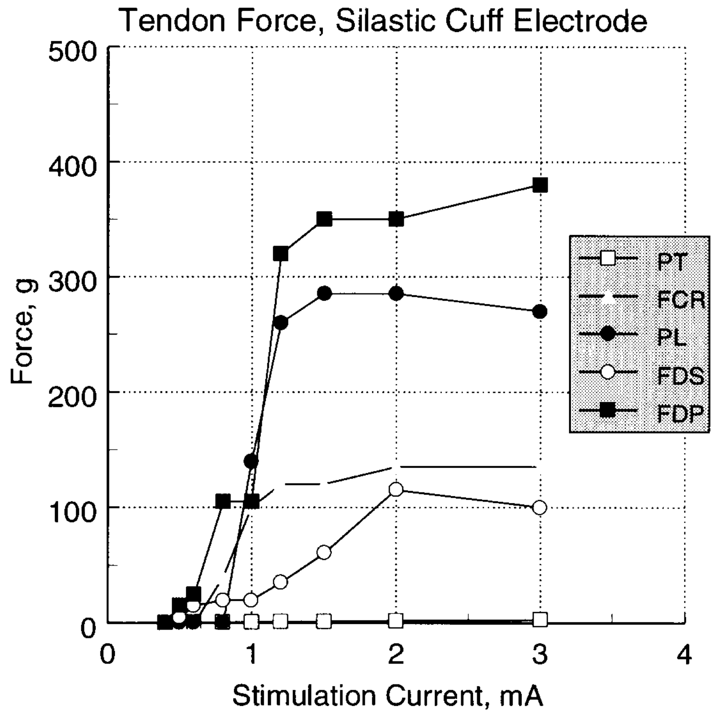

Figure 2. Selective stimulation with a silastic cuff electrode: tendon force as a function of stimulation current for 5 muscles in the raccoon forearm.

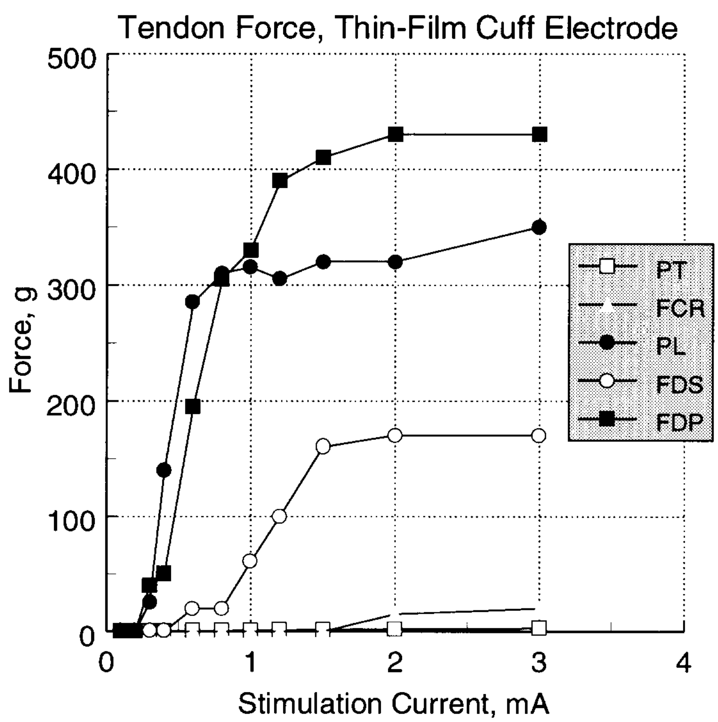

Figure 3. Selective stimulation with a FEP Teflon cuff electrode: tendon force as a function of stimulation current for 5 muscles in the raccoon forearm.

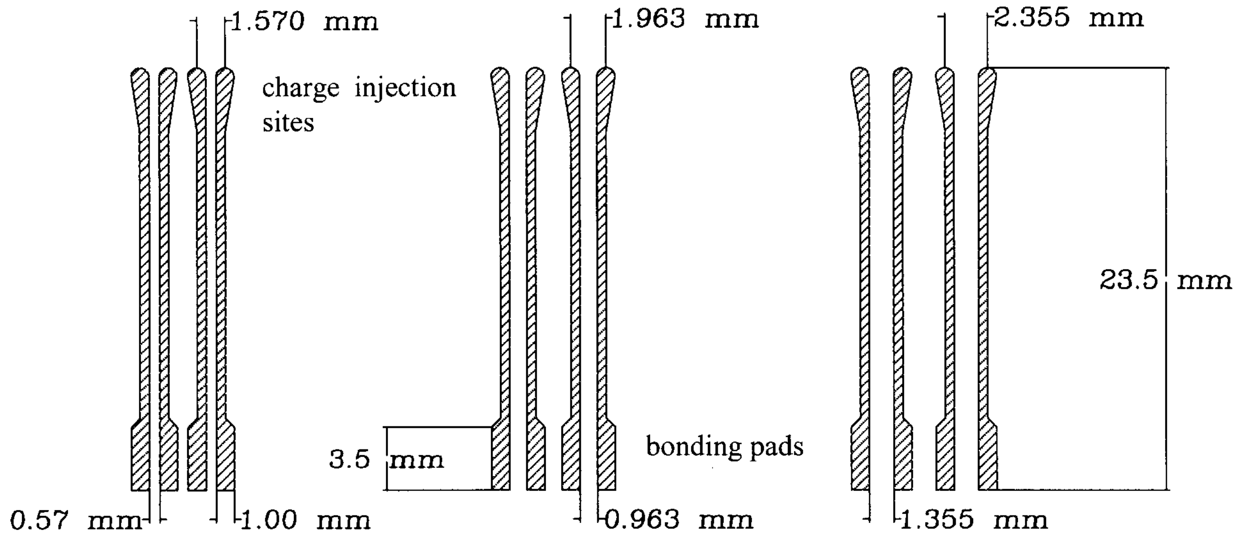

Figure 4. Metallization patterns for a cuff electrode with four charge injection sites arranged circumneurally with each electrode spaced at an angle of 90°. The nerve runs top-to-bottom as drawn with ~1 mm around the charge injection being thermoformed into a cuff.

of the initial CV with that taken after 15 minutes for an electrode site is shown in Fig. 5. A minor amount of activation is apparent from the oxide peaks forming in the 0.1-0.2 V vs Ag/AgCl potential range. All four sites on the electrode were treated in the same manner and

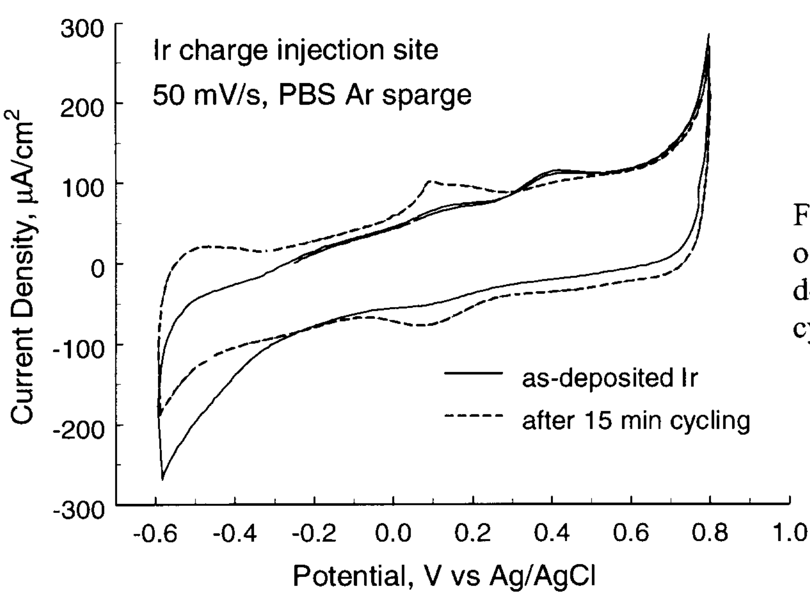

Figure 5. Cyclic voltammograms of an Ir charge injection site, as-deposited and after 15 minutes of cycling in PBS.

exhibited similar CV behavior. No additional activation was used with this first chronic electrode.

One electrode was implanted in the left upper arm of a raccoon with both branches of the median nerve and the ulnar nerve running through the cuff. The nerves were exposed and isolated from the surrounding fascia. Using an insertion tool, the cuff was positioned around the nerves about 9 cm proximal of the elbow. There was no fixation to the epineurium of the nerve. The contralateral nerves were exposed and separated from the fascia without implanting an electrode. The electrode leads were tunneled to the back and brought out through a trocar hole. An acute, qualitative evaluation of the functional response of the cuff was made by monopolar stimulation of each electrode site using a remote, needle electrode in the shoulder. The response of the paw and forearm were observed visually for a range of stimulation currents. The observations are described in Table 1.

Table 1. Functional response of the volar forearm to stimulation with a four-electrode nerve cuff implanted around the median and ulnar nerves in the upper forearm.

Electrode Location	Threshold function, mA	Intermediate function, mA	Maximal function, mA
0°	wrist, 0.7	elbow, wrist, digit, 1	elbow, wrist, digit, 3
90°	wrist, digit, 1	wrist, digit, 2	elbow, wrist, digit, 6
180°	digit, 0.7	wrist, digit, 2	elbow, wrist, digit, 4
270°	wrist, digit, 0.7	elbow, wrist, digit, 2	elbow, wrist, digit, 6

While observing the paw, a threshold response was defined by the first perceptible movement; the maximal response was defined by the current level beyond which further increases induced no additional paw or forelimb movements; and, intermediate was defined by the current level that produced approximately half the maximal movement.

Stimulation with the monopolar, circumneural configuration was less selective in this animal compared with previous studies in which longitudinal tripolar electrodes were used on the deep and superficial branches of the median nerve without inclusion of the ulnar. Most notable is the absence of pronation. There was some selectivity between wrist and digit flexion for the 0° and 180° electrodes near threshold. The responses at higher current levels with all four electrodes were otherwise similar.

At the writing of this report, the animal has been implanted for 5 weeks. The animal uses his paws normally and there is no evidence of foot drop or other indications of nerve damage. After 6 weeks of implantation, the functional responses will be reevaluated and the animal sacrificed for histological evaluation of the implant site.

3.0 FUTURE WORK

A third electrode design is in process. The geometry of this electrode will be modified to simplify the implantation procedure and further reduce the likelihood of mechanical damage during chronic implantation. We anticipate implanting three raccoons with these electrodes.